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Estimation of aerosol properties over the Chinese desert region with MODIS AOD assimilation in a global model

YIN Xiao-Mei [a,b], DAI Tie [a,c,*], XIN Jin-Yuan [d], GONG Dao-Yi [e], YANG Jing [e], TERUYUKI Nakajima [f], SHI Guang-Yu [a]

[a] State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

[b] College of Earth Science, University of the Chinese Academy of Sciences, Beijing 100029, China

[c] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing 210044, China

[d] State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

[e] State Key Laboratory of Earth Surface Processes and Resource Ecology (ESPRE), Beijing Normal University, Beijing 100029, China

[f] Earth Observation Research Center, Japan Aerospace Exploration Agency, Tsukuba 305-8555, Japan

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Abstract

A Local Ensemble Transform Kalman Filter assimilation system has been implemented into an aerosol-coupled global nonhydrostatic model to simulate the aerosol mass concentration and aerosol optical properties of 3 desert sites (Ansai, Fukang, Shapotou) in northwestern China. One-month experiment results of April 2006 reveal that the data assimilation can correct the much overestimated aerosol surface mass concentration, and has a strong positive effect on the aerosol optical depth (AOD) simulation, improving agreement with observations. Improvement is limited with the Ångström Exponent (AE) simulation, except for much improved correlation coefficient and model skill scores over the Ansai site. Better agreement of the AOD spatial distribution with the independent observations of Terra (Deep Blue) and Multi-angle Imaging Spectroradiometer (MISR) AODs is obtained by assimilating the Moderate Resolution Imaging Spectroradiometer (MODIS) AOD product, especially for regions with AODs lower than 0.30. This study confirms the usefulness of the remote sensing observations for the improvement of global aerosol modeling.

Keywords: Aerosol properties; Aerosol assimilation; Moderate Resolution Imaging Spectroradiometer; Multi-angle Imaging Spectroradiometer; PM_{10}

1. Introduction

Aerosols have been in the climate research spotlight because of their direct and indirect impacts on radiative balance and their interaction with other earth systems such as clouds (Forster et al., 2007). In addition to the important ground-based observation networks, satellite platforms such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Imaging Spectroradiometer (MISR) provide various global observations of aerosol optical depth (AOD), which is a measure of light extinction by aerosols in the atmospheric column above the Earth's surface (Levy et al., 2013; Ma et al., 2016; Sayer

* Corresponding author. State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

E-mail address: daitie@mail.iap.ac.cn (DAI T.).

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et al., 2013; van Donkelaar et al., 2010, 2015). In addition, numerical simulation and prediction have offered a more global view of aerosol emission, transport and interaction with nonlinear physical processes than the observations. Uncertainties still remain in estimating the radiative effect of aerosols, although research is in progress using both observational and numerical approaches. Considering the perceived inadequacies of models, the data assimilation system that combines model output with observations to obtain a weighted mean, which is much closer to the actual, improves aerosol predictions and provides a consistent framework for assessing various model error sources (Liu et al., 2011; Schutgens et al., 2010a, 2010b). Collins et al. (2001), Yu et al. (2003), and Adhikary et al. (2008) utilized the Optimal Interpolation to assimilate AODs in both regional and global chemical transport models. Using the three-dimensional variational method (3D-var), AODs of POLarization and Directionality of the Earth's Reflectances (POLDER), Along Track Scanning Radiometer (ATSR) and MODIS have been assimilated (Henzing, 2005; Generoso et al., 2007; Niu et al., 2008). In both the Optimal Interpolation and 3D-var techniques, the model error covariant structure has to be assumed a priori and is usually constant in space or time. Therefore, a 4D-var and Ensemble Kalman filter (ENKF) were developed for aerosol assimilation to represent the varying spatiotemporal model covariance, estimate the posterior error, and generate the analysis ensemble (Evensen, 1994; Whitaker and Hamill, 2002; Benedetti et al., 2009). Recently, new attempts for assimilation have been developed. Liu et al. (2011) and Pagowski et al. (2014) implemented the Gridpoint Statistical Interpolation (GSI) 3D-var data assimilation system and its extension for assimilating the surface measurements of $PM_{2.5}$, PM_{10}, and MODIS AOD satellite data. The Local Ensemble Transform Kalman filter (LETKF) was applied to global aerosol transport for assimilating AErosol RObotic NETwork (AERONET) and MODIS data (Hunt et al., 2007; Schutgens et al., 2010a, 2010b; Dai et al., 2014b). The Chinese desert is regarded as one of the largest sources of Asian dust aerosols, and a lot of results on the dust emissions, optical properties, and effects on the climate system have been obtained by observation and simulation (Wang et al., 2012; Che et al., 2013; Wang and Niu, 2013; Yu et al., 2015; Zong et al., 2015).

Suzuki et al. (2008) implemented a global three-dimensional aerosol transport-radiation model SPRINTARS (Spectral Radiation Transport Model for Aerosol Species) in NICAM (Nonhydrostatic ICosahedral Atmospheric Model) to perform a simulation using the Earth Simulator. In our previous studies, the global aerosol optical properties were simulated and evaluated using the standard NICAM-SPRINTARS, which were also validated with AERONET and MODIS data (Dai et al., 2014a, 2015). Furthermore, the sensitivity tests of the LETKF assimilation system were performed by assimilating AERONET and MODIS data, respectively. And the aerosol optical properties, simulated by the NICAM-SPRINTARS with and without the data assimilation, have been validated on a global scale or over East Asia (Schutgens et al., 2010a, 2010b; Dai et al., 2014b). In this paper, the LETKF methodology is applied to the NICAM-SPRINTARS, to study aerosol properties over the Chinese desert region, and analyze the differences and improvements in the model simulations without (standard) and with data assimilation. The simulated results are validated by independent observations from MODIS Collection 6 (Deep Blue), MISR Level 3, and ground-based observations offered by our cooperators.

2. Data and model description

In this study, we use the NICAM-SPRINTARS model as the forecast model for the assimilation system of the LETKF methodology (Hunt et al., 2007). The forecast model predicts the mass mixing ratios of the major tropospheric aerosols (sulfate, carbonaceous aerosols including BC and OC, sea salt, and soil dust) (Takemura et al., 2000; Takemura and Nakajima, 2002). In this study, the mass mixing ratios are adjusted by assimilating the United States Naval Research Laboratory (NRL) MODIS Level-3 (L3) AOD products (Zhang and Reid, 2006). In the assimilation experiment, the ensemble size is assigned to ten members, the perturbation factors are performed spatiotemporally dependent, and the local patch size is set to 1500 km (Dai et al., 2014b). The model wind, water vapor, pressure, and temperature fields are nudged to the NCEP Final (FNL) analysis data over a timescale of 6 h. The aerosol emission inventories come from the anthropogenic sources of the AeroCom Phase-II dataset, while the dust and sea salt emissions depends on the near-surface wind speed, vegetation, soil moisture, leaf area index, and amount of snow and ice (Takemura et al., 2009).

The statistical metrics, including the correlation coefficient (R), and the skill score (S) are used to evaluate the model performance.

$$S=\frac{4(1+R)}{(D+1/D)^2(1+R_0)} \tag{1}$$

S is a relatively comprehensive statistical index for model simulation, D is the ratio of the standard deviation of the model to that of the observation, and R_0 is the maximum attainable R, which is set to 1 (Taylor, 2001; Chin et al., 2009; Dai et al., 2014a). The independent validation observations are the PM_{10} grid data (0.5° × 0.5°) offered by Guo (2014), the Chinese Sun Hazemeter Network (CSHNET) data offered by Xin et al. (2007), the monthly MODIS Collection 6 Deep Blue AOD (Terra) at 550 nm (Hsu et al., 2013), and the global monthly MISR Level3 retrievals (http://dx.doi.org/10.5067/Terra/MISR/MIL3MAE_L3.004) (Diner et al., 2001; Liu et al., 2004, 2010; Kahn et al., 2010). CSHNET is the first standard network established to measure aerosol optical properties and their spatiotemporal variations throughout China. Fig. 1 shows the spatial distribution of 3 CSHNET sites: Ansai, located in the Loess Plateau in Shaanxi province, where mineral dust aerosols are emitted due to the intensive farming and the exposure of bare soil; Fukang, located in glacial to desert transition zone, where agricultural and pastoral activities take place; and Shapotou, situated in an arid part of the Tengger Desert with more persistent dust aerosols.